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1

LA-UR -89-2915

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LA-UR--89-2915

DE89 016609

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SUBMITTED TO: Eleventh International Free Electron Laser Conference
Naples, Florida
August 28 September 1, 1989

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MASTER

FORM NO 836 R4
ST NO 2629 5/81

STABILITY REQUIREMENTS OF RF LINAC-DRIVEN FREE-ELECTRON LASERS*

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Abstract

Fluctuations in the output power and wavelength have been observed in two high-power, RF-driven, free-electron lasers (FELs): (1) the 10-μm FEL that has operated at the Los Alamos National Laboratory and (2) the visible FEL at the Boeing Physical Sciences Research Center. The fluctuations have been traced primarily to instabilities in the electron beam. Specifically, these are variations in the electron energy, the charge per micropulse, and the time interval between micropulses. The effects of these instabilities on the performance of one of the FELs is demonstrated. Efforts made to minimize these instabilities are discussed and the subsequent improvements in the operation of each of the FELs are presented.

1. Introduction

The performance of free-electron lasers (FELs) depends on the properties of the incident electron beam. For FELs driven by an electron beam from an RF linear accelerator, the stability of each of the following is crucial: the electron energy, the charge per micropulse, and the time interval between micropulses. This limitation places severe stability requirements on the RF systems and the electron gun pulser.

*Work supported and funded by the US Department of Defense, Army Strategic Defense Command under the auspices of the US Department of Energy.
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In particular, the fluctuations in the phase and amplitude of the RF must be less than a small fraction of a degree and much less than a percent, respectively. Likewise, the variations of the time between electron pulses and the charge per pulse must be less than a picosecond and much less than a percent in amplitude. At the Los Alamos National Laboratory, an infrared FEL has been operated for many years, and at the Boeing Physical Science Research (BPSRC) a visible FEL is now operational. Considerable effort has been made at both facilities to minimize the instabilities in these parameters. The stability requirements for the shorter-wavelength BPSRC experiment are particularly severe.

In this paper, we briefly describe the FELs at the two facilities, the stability requirements that were thought to be necessary. We demonstrate the sensitivity of lasing to these instabilities and describe diagnostic techniques used to measure time fluctuations in the picosecond regime. We also discuss the success in improving the performance of these lasers.

2. Accelerator descriptions

The Los Alamos accelerator shown in fig. 1 consists of an injector, subharmonic buncher, a fundamental frequency buncher, two standing-wave accelerating structures, and two klystron RF systems. The injector contains a thermionic triode gun and the required electronics to produce a group of 2000 electron bunches at a frequency of 21.67 MHz and an energy of 80 keV. Each individual bunch from the gun has a duration of about 3 ns and is called a micropulse. The group of micropulses, about 100 μs in duration, is repeated once a second in normal operation and is called a macropulse. The micropulses are bunched in the bunchers and the first cavities of the accelerator to provide electron pulses with a duration of about 40 ps and a peak current of about 100 A. The subharmonic buncher operates at a frequency of

108.33 MHz, which is the 12th subharmonic of the 1.3-GHz fundamental frequency. These electron pulses are accelerated in two, tandem, side-coupled, standing-wave linear accelerating structures to a nominal energy of 20 MeV, although operation down to 10 MeV has been accomplished. Further bunching in the 60° bending magnets provides electron pulses at the wiggler with a duration of about 10 ps and a peak current of a few hundred amperes.

The BPSRC accelerator shown in fig. 2 is considerably larger and consists of an injector with a thermionic gun, two subharmonic bunchers, a tapered-phase buncher, and six traveling-wave accelerating structures each with a klystron RF system. In this linac, the time interval between micropulses is about 260 ns and the macropulse is usually 110 μs long. The electron pulses from the gun are about 2 ns in duration and are subsequently bunched to about 10 ps in the subharmonic bunchers and the tapered-phase section. These electron pulses are then accelerated to an energy of 110 MeV in the six accelerating structures. Typically, the electron charge is 3 nC per micropulse.

A series of magnets bends the electron beam 180° into the optical cavity.

3. Electron-beam stability requirements and previous measurements

Previously, estimates of the beam stability requirements [1] were made as follows:

- **Energy:** Spread $< 0.5\%$ because of width of gain curve for a 1-m long wiggler.
  Variation $< 0.1\%$ to minimize output power fluctuations.
- **Current:** 0.1% to minimize energy variations due to beam loading.
- **Temporal:** Micropulse duration of at least 10 ps to minimize slippage.
  Interval jitter $<$ 0.5 ps/micropulse to provide optimum overlap of the electron and optical micropulses.

Previous measurements [2] indicated that the fluctuations observed in the Los Alamos FEL were caused primarily by noise in the electron-gun pulser and the klystron amplifier chains. This reference states that the high-frequency noise is eliminated by the filtering action of the accelerators, which have a filling time of 2 μs. This is correct only for RF drive phase and amplitude fluctuations. Variations in the charge per micropulse from the gun can and do cause beam loading fluctuations that are not filtered by the response time of the accelerators. These fluctuations can occur from one micropulse to another, i.e., at the micropulse rate. Recovery from these rapid beam-loading variations can only occur at a slower rate dependent on the fill time of the accelerators and the response time of the RF control system. Therefore, it is essential that the electron-gun pulser be stabilized on a time scale comparable to the time interval between micropulses.

4. Diagnostics

At Los Alamos, the slow and fast deflectors [3] have been useful in determining the energy variation during the macropulse and the variation of the time interval between micropulses.

Another method has been useful in observing the micropulse time jitter in the gun, buncher, and accelerators. The technique consists of adding a portion of the 1.3-GHz fundamental frequency from the master oscillator to the micropulse signal from an electron-beam current monitor.* With the amplitude of the RF properly adjusted, dots appear on the micropulse signal for each RF cycle. By adjusting the RF phase, one or more dots can be made to occur on the rise of the micropulse signal. A time calibration is obtained from the RF period or from a phase shifter in the RF

* Two 7A29 amplifiers in a Tektronix Mod. 7104 oscilloscope operated in the add mode provides an adequate system.

signal cable. This technique is most applicable for micropulses that are uniform in amplitude during the useful portion of the macropulse.

This technique is illustrated in fig. 3 where the time variation between micropulses and the time slew during a macropulse is displayed for the Los Alamos thermionic gun. From these data, the time slew is estimated to be 69 ps in the last 80 μs of the macropulse, and the time jitter between micropulses is about 38 ps.

The time variation of the micropulses decreases as the electron bunches traverse the subharmonic buncher, fundamental buncher, and the first accelerator. In the Los Alamos accelerator, the time jitter and slew are reduced by a factor of about 25.

5. Sensitivity of lasing to RF instabilities

Although considerable effort has been expended to stabilize the RF fields in the accelerating structures, occasionally a transient change in the phase or amplitude occurs with a deleterious effect on the lasing. Fig. 4 gives an example of such effects in the Los Alamos FEL. In one case (fig. 4a), two noise pulses appeared on the RF phase in the first accelerator. One of the pulses with a 0.5° change in phase caused the lasing power to change about 20% and another of 1.3° changed the laser power 40%. In the second case (fig. 4b), the RF power in the second accelerator decreased 2.4% half-way through the macropulse causing a 1 2% change in the RF fields in the second accelerating structure and a 0.6% decrease in the overall electron energy from both accelerators. This almost turned off the lasing and resulted in at least a 70% decrease in the lasing power.

These results are consistent with the stability requirements given in Section 3 for laser power stability of a few percent.

6. Modification to the linac at BPSRC

Considerable efforts were made to improve the performance of the BPSRC linac. These efforts included stabilizing the amplitude of the gun pulses, controlling the phase and amplitude of the fields in both subharmonic bunchers, and, in addition, working on the stability of the RF systems driving each of the accelerators.

Feedback was installed on the gun pulser to provide constant amplitude of the micropulses during the macropulse. Before stabilization, the micropulse amplitude decreased about 10% during the last 80% of the macropulse. After the stabilization, the pulse height decrease was less than 1% over the same part of the macropulse as sho 'n in fig. 5.

Feedback systems were installed on each of the subharmonic bunchers to control the phase and amplitude of the cavity fields. RF signals, proportional to the cavity fields, were obtained from coupling loops installed in each of the buncher cavities. These signals were compared to a master oscillator signal in a feedback circuit that provides proportional and integral control of the RF amplifiers. The controllers reduced the amplitude variations from about 10% to less than 1% and the phase instabilities of about 8° to less than 0.7°.

Further stabilization of the klystron RF systems was also accomplished. Each system contains a pulse forming network (PFN) that initially provided a 250-μs pulse with a 1-μs rise time. The PFN was modified to give a 10-μs rise time, thereby reducing the variations and ringing of the high-voltage pulse. With additional tuning of the PFN, the pulse on the klystron is now flat to about 0.5%. The feedback system has been redesigned to include both integral and proportional control as well as higher closed-loop gain with a smaller bandwidth. Improvement in the phase stability is shown in fig. 6 where the vertical scale is 1° per division. Fig. 7 shows the

RF amplitude stability after the improvements, where the vertical scale is 2.8% per division. In each case, the horizontal scale is 20 μs.

With these improvements to the gun pulser and the RF systems as well as repositioning a magnet in the beam line from the last accelerator to the wiggler, the performance of the laser has improved considerably. The laser energy per micropulse has increased from about 1 μJ to about 50 μJ.

References

1. W. E. Stein et al., IEEE J. Quantum Elec. QE-21, 889 (1985).
2. M. T. Lynch et al., IEEE J. Quantum Elec. QE-21, 904 (1985).
3. R. L. Sheffield et al., IEEE J. Quantum Elec. QE-21, (1985).

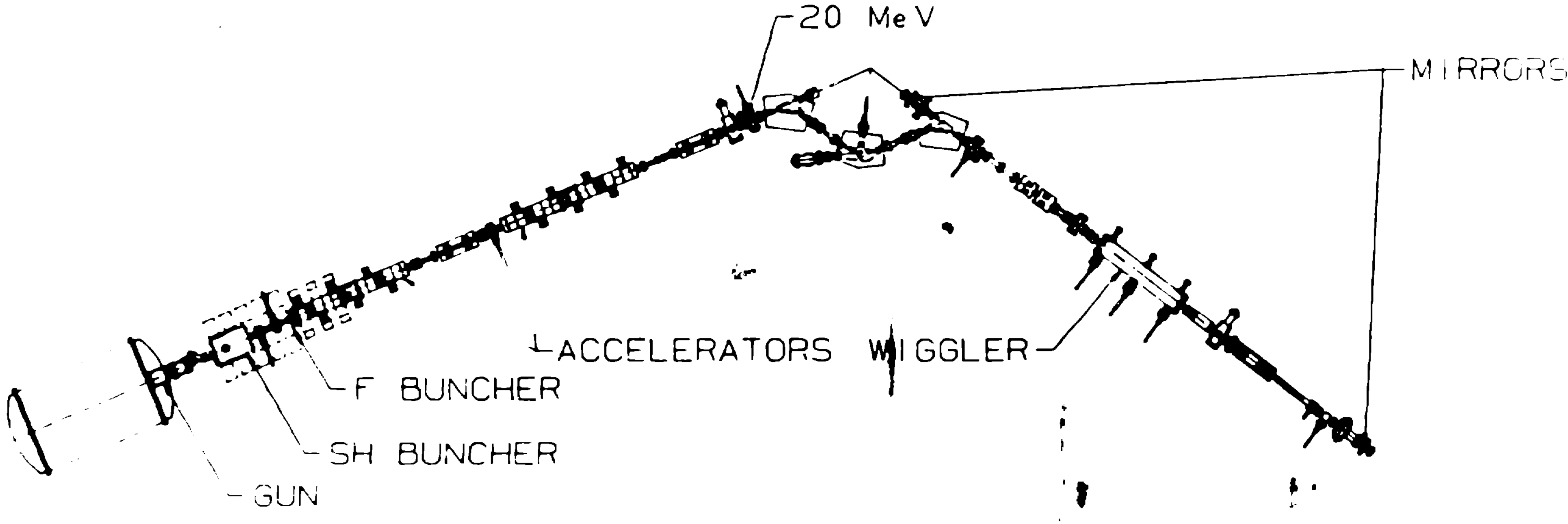
Figure Captions

1. Configuration of the LANL FEL.
2. Arrangement of the BPSRC FEL.
3. Time slew and jitter of the LANL electron gun pulses. The upper left picture shows the time slew for the complete macropulse with 20 μs/horizontal division. The vertical scale is about 250 ps per division. The upper right picture shows the time jitter in the middle of the macropulse with 1 μs/horizontal division and the same vertical scale. The lower picture shows the individual micropulses with the dots on the leading edge caused by the 1.3-GHz signal as described in the text. The horizontal scale is 20 ns/division and the same vertical scale.
4. Sensitivity of lasing to variations in RF phase and amplitude in the Los Alamos FEL.

a) The top and bottom traces of the left picture show the phase of the first and second accelerators, respectively. Two instabilities occurred in the top trace. The first was about 0.5° and the second was about 1.3°. These fluctuations caused 20% and 40% changes in the laser power as shown in the picture on the right.

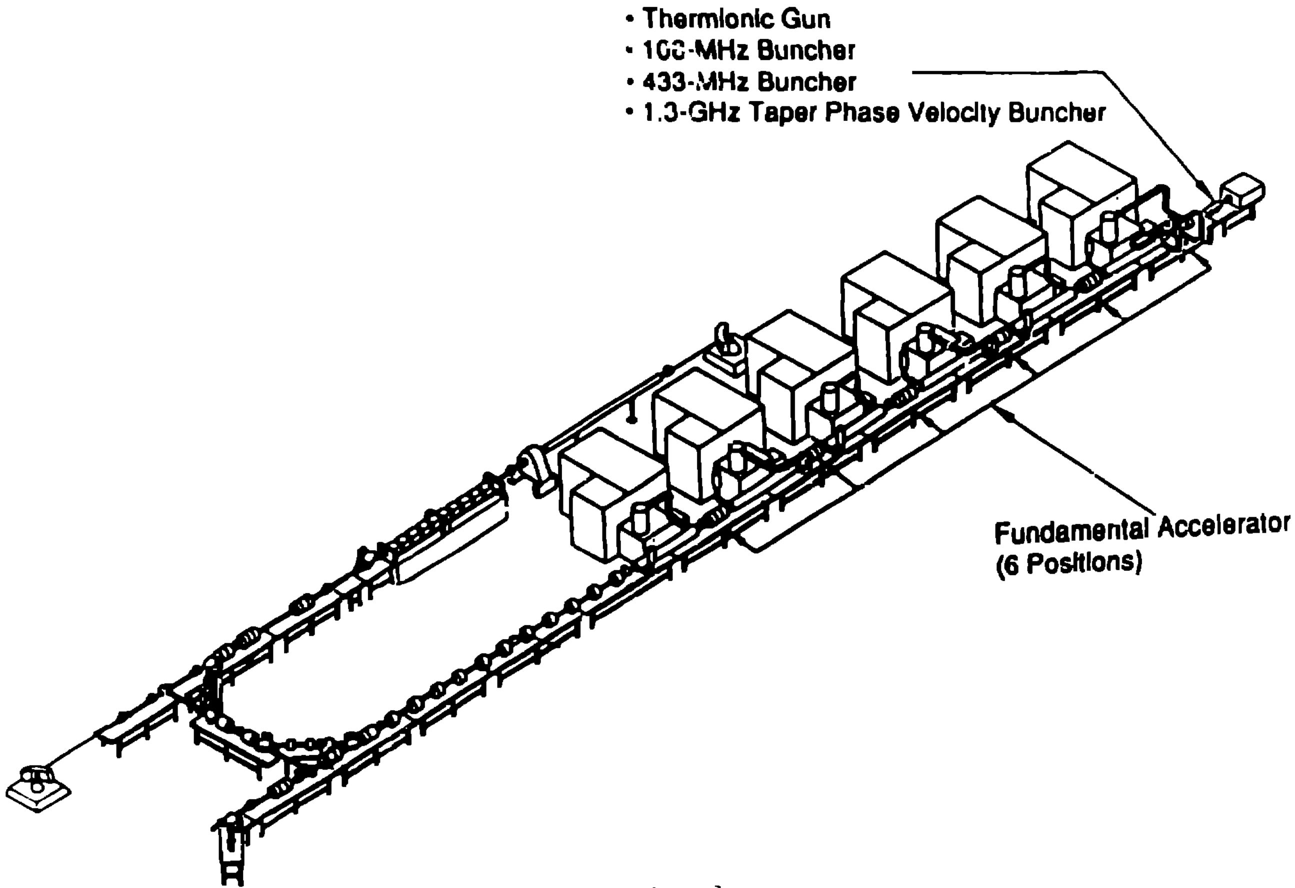
b) The bottom left picture shows a decrease in RF power in the second accelerator of 2.4% resulting in a 1.2% decrease in the RF fields in that accelerating structure and a 0.6% change in the electron energy. The effect on the lasing power is shown in the picture on the right. The horizontal scale is 20 μs/division.

5. BPSRC thermionic gun macropulse after amplitude control. The vertical scale is 1.25 nC per division and the horizontal scale is 20 μs per division.
6. Phase of the klystron RF during a macropulse after stabilization of the klystron voltage and installation of feedback control on the RF. The vertical scale is 1° per division and the horizontal scale is 20 μs per division.
7. Amplitude of the klystron RF during a macropulse after stabilization of voltage and installation of feedback control on the RF. The vertical scale is about 2.8% per division and the horizontal scale is 20 μs per division.



LOS ALAMOS 10-MICRON FEL

Fig 1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• 100-MHz Buncher
• 433-MHz Buncher
• 1.3-GHz Taper Phase Velocity Buncher
Fundamental Accelerator
(6 Positions)

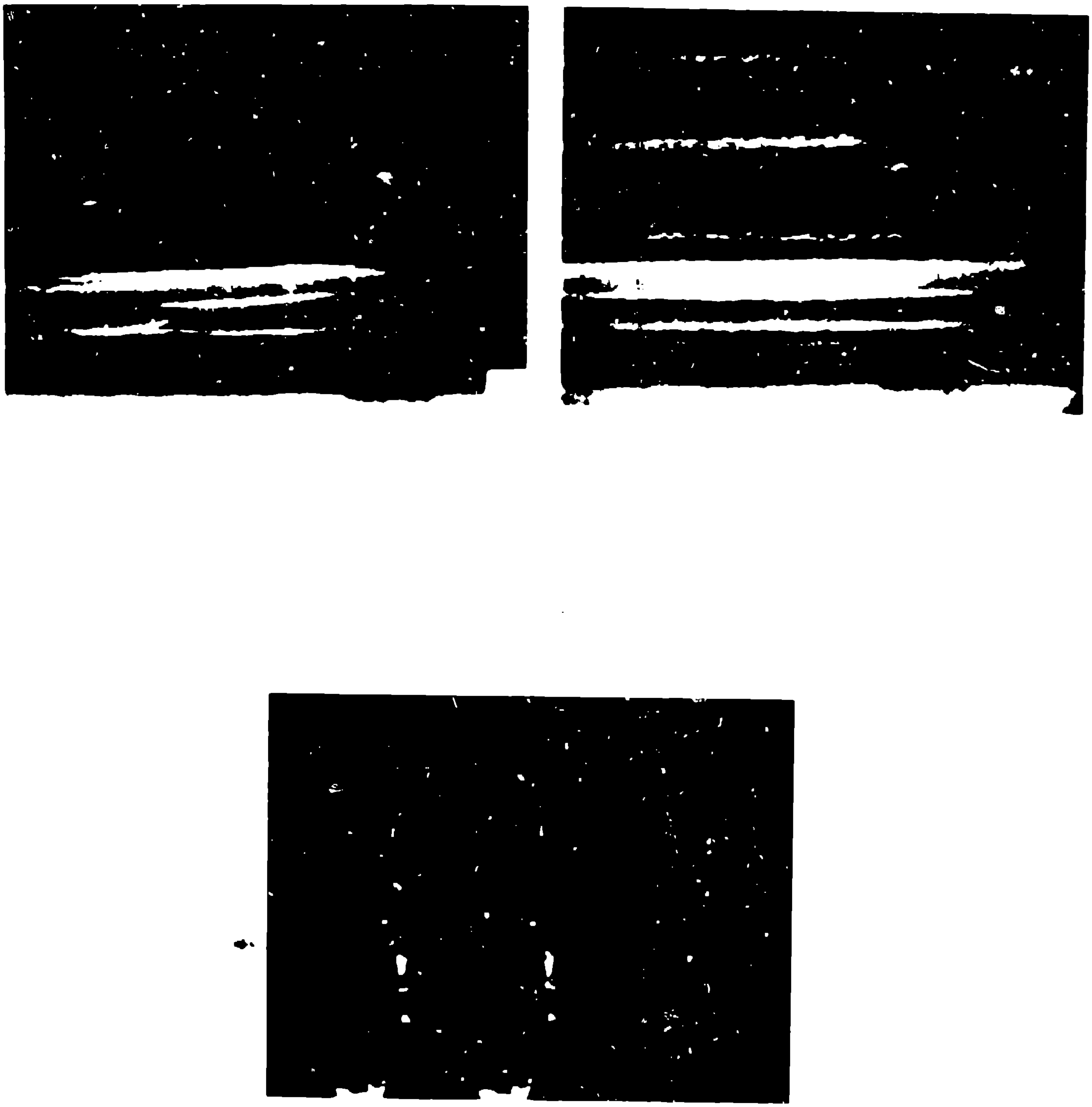
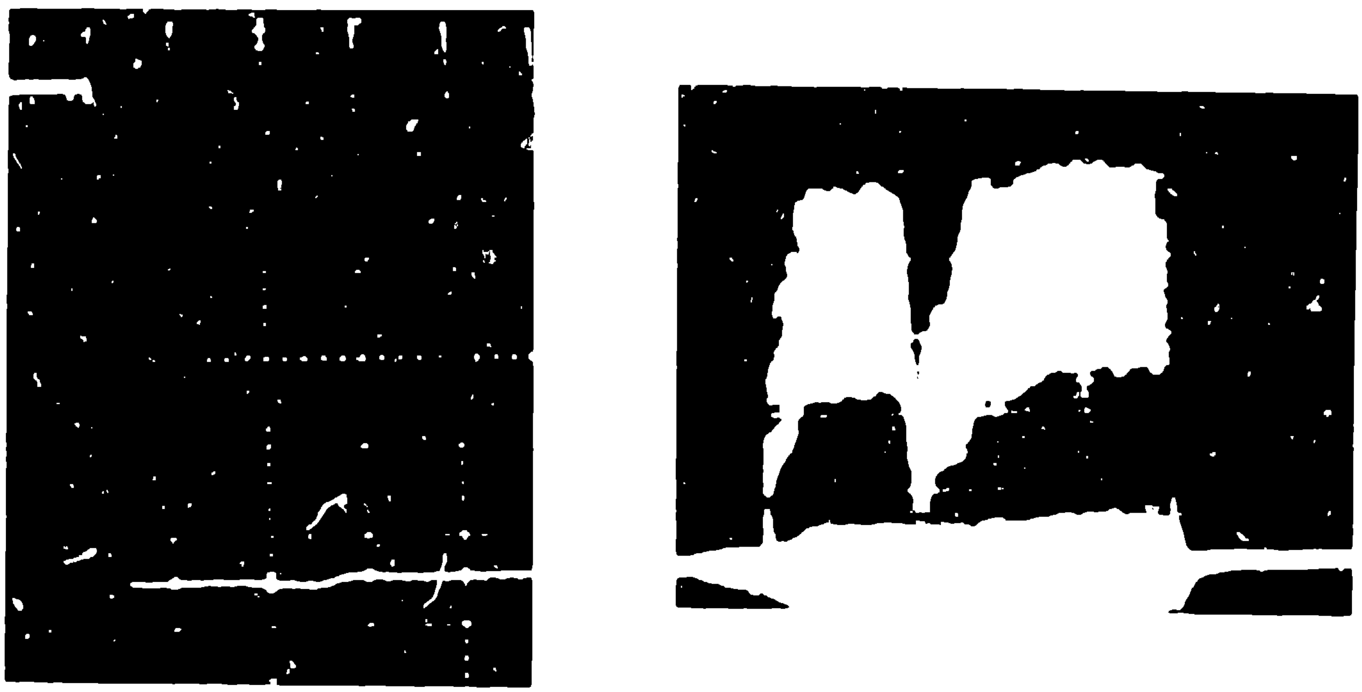


Fig. 3

A



B

Fig. 6

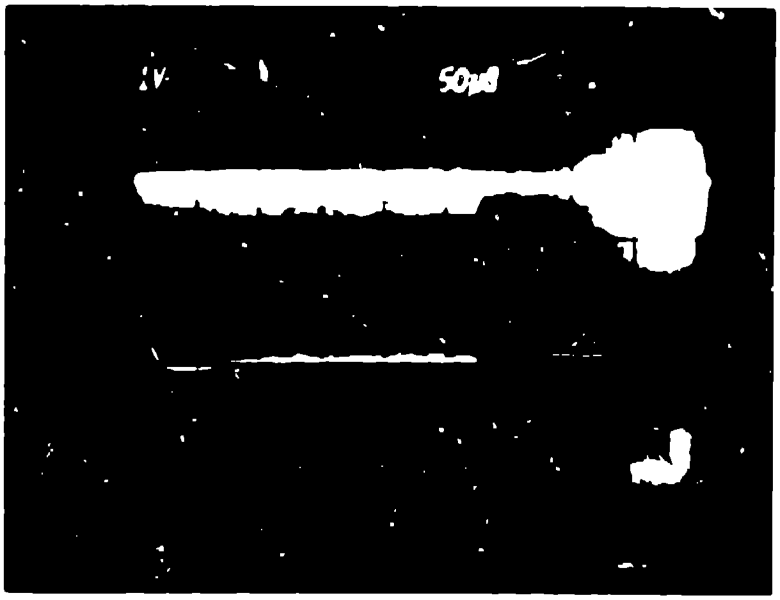


Fig. 5

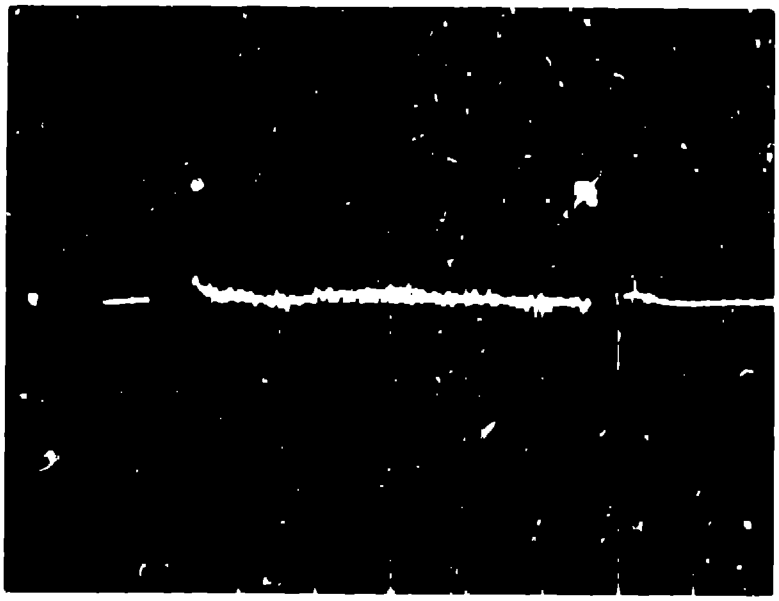


Fig. 6

Fig. 7